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# Non-Standard Neutrino Interactions and Neutrino Oscillation Experiments

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## Abstract

In analyzing neutrino oscillation experiments it is often assumed that while new physics contributes to neutrino masses, neutrino interactions are given by the Standard Model. We develop a formalism to study new physics effects in neutrino interactions using oscillation experiments. We argue that the notion of branching ratio is not appropriate in this case. We show that a neutrino appearance experiment with sensitivity to oscillation probability  $P_{ij}^{exp}$  can detect new physics in neutrino interactions if its strength  $G_N$  satisfies  $(G_N/G_F)^2 \sim P_{ij}^{exp}$ . Using our formalism we show how current experiments on neutrino oscillation give bounds on the new interactions in various new physics scenarios.

## I. INTRODUCTION

The goal of neutrino oscillation experiments is to probe those extensions of the Standard Model (SM) which predict non-vanishing neutrino masses. However, in the usual treatment of neutrino oscillation experiments, it is often assumed that neutrino interactions are described just by the SM [1]. While we know that this is a good approximation, often physics beyond the SM induces also new neutrino interactions. If New Physics (NP) contributes significantly to neutrino interactions, the conclusions that we draw from the experimental data can be affected. For example, even for massless neutrinos, the NP can allow for weak eigenstate muon neutrino to produce an electron in the detector, and in this case, we may erroneously conclude that oscillations have occurred.

To search for NP effects in massive fermion interactions (quarks and charged leptons) the experimentally measured branching ratios are used in a straightforward way. However, in the case of neutrinos, there are two important subtleties:

- Neutrino masses are unknown, and their difference may be very small. In such a case, experiments cannot observe neutrinos as mass eigenstates, and the results are sensitive to the time evolution of the flavor eigenstates.
- The neutrino flavor is identified by charged current interactions. Since NP may modify them, the identification of the neutrinos cannot be done in a model independent way.

The results of neutrino oscillation experiments are sensitive to the following three ingredients: The production process, the time evolution and the detection process. It is impossible to separate the NP contributions to the neutrino production or detection process: a formalism that combines all the three ingredients is necessary.

## II. FORMALISM

For simplicity, and without loss of generality, we assume two neutrino flavors, CP conservation and that the neutrinos are highly relativistic. First, we define the bases we use. Since the mass basis is well defined, we express all neutrino states as superpositions of mass eigenstates. We always work in the mass basis for the charged leptons. Then, the weak interactions define the weak basis where the neutrino weak eigenstates are  $SU(2)$  partners of the charged leptons. We start with a specific example and generalize it later. We consider a muon neutrino beam produced by  $\pi \rightarrow \mu\nu$  decay, and the subsequent detection of electron neutrinos through  $\nu n \rightarrow ep$ . The weak eigenstate  $|\nu_\mu^W\rangle$ , is given by a superposition of mass eigenstates  $|\nu_\alpha^m\rangle$  as

$$|\nu_\mu^W\rangle = \sum_\alpha U_{\mu\alpha}^W |\nu_\alpha^m\rangle, \quad (1)$$

so that  $|U_{\mu\alpha}^W|^2 \propto |\langle \nu_\alpha^m, \mu | \mathcal{H}^W | \pi \rangle|^2$  where  $\mathcal{H}^W$  is the weak interaction Hamiltonian. In the presence of NP there might be extra carriers of the charged current interaction besides the  $W$  boson. Therefore, the neutrino produced by  $\pi \rightarrow \mu\nu$  may be different from  $|\nu_\mu^W\rangle$ . We define this neutrino as a source basis eigenstate  $|\nu_\mu^s\rangle$ , given by a different superposition of mass eigenstates

$$|\nu_\mu^s\rangle = \sum_\alpha U_{\mu\alpha}^s |\nu_\alpha^m\rangle, \quad (2)$$

so that  $|U_{\mu\alpha}^s|^2 \propto |\langle \nu_\alpha^m, \mu | \mathcal{H} | \pi \rangle|^2$ ,  $\mathcal{H} = \mathcal{H}^W + \mathcal{H}^{NP}$  where  $\mathcal{H}^{NP}$  is the NP interaction Hamiltonian. Similarly, we define the neutrino detected by  $\nu n \rightarrow ep$  as a detector basis eigenstate  $|\nu_e^d\rangle$ , given by another superposition of mass eigenstates

$$|\nu_e^d\rangle = \sum_\alpha U_{e\alpha}^d |\nu_\alpha^m\rangle, \quad (3)$$

so that  $|U_{e\alpha}^d|^2 \propto |\langle \nu_\alpha^m, n | \mathcal{H} | e, p \rangle|^2$ .

In general, for any neutrino oscillation experiment it is useful to use the following bases:

- The mass basis,  $\{|\nu_\alpha^m\rangle\}$ , where the neutrino mass matrix is diagonal.
- The weak basis,  $\{|\nu_\alpha^W\rangle\}$ , where the leptonic couplings of the  $W$  are diagonal.
- The source basis,  $\{|\nu_\alpha^s\rangle\}$ , where the interaction of the production process is diagonal.
- The detector basis,  $\{|\nu_\alpha^d\rangle\}$ , where the interaction of the detection process is diagonal.

When neutrino interactions are fully described by the SM, the last three definitions coincide, and this basis is usually called the interaction or the flavor basis. However, the main lesson from the above discussion is that in the presence of NP those three bases can be different.

The source and the detector bases are related to the mass basis through the unitarity transformations

$$|\nu_\ell^s\rangle = \sum_\alpha U_{\ell\alpha}^s |\nu_\alpha^m\rangle, \quad |\nu_\ell^d\rangle = \sum_\alpha U_{\ell\alpha}^d |\nu_\alpha^m\rangle, \quad (4)$$

with  $\ell = e, \mu, \tau$ . The amplitude for finding a  $\nu_n^d$  in the original  $\nu_\ell^s$  beam at time  $t$  is

$$\langle \nu_n^d | \nu_\ell^s \rangle(t) = \sum_{\alpha, \beta} \langle \nu_\beta^m | U_{\beta n}^{d\dagger} e^{-iE_\alpha t} U_{\ell\alpha}^s | \nu_\alpha^m \rangle = \sum_\alpha e^{-iE_\alpha t} U_{\ell\alpha}^s U_{n\alpha}^{d*}, \quad (5)$$

where in the last step we have used the orthogonality of the mass eigenstates. The probability of finding a  $\nu_n^d$  in the original  $\nu_\ell^s$  beam at time  $t$  is

$$\begin{aligned} P_{n\ell}(t) &= \left| \langle \nu_n^d | \nu_\ell^s \rangle(t) \right|^2 = \left( \sum_\alpha e^{-iE_\alpha t} U_{\ell\alpha}^s U_{n\alpha}^{d*} \right) \left( \sum_\beta e^{iE_\beta t} U_{\ell\beta}^{s*} U_{n\beta}^d \right) \\ &= \sum_{\alpha, \beta} \left| U_{\ell\alpha}^s U_{\ell\beta}^{s*} U_{n\alpha}^{d*} U_{n\beta}^d \right| \cos \left[ (E_\alpha - E_\beta)t - \arg \left( U_{\ell\alpha}^s U_{\ell\beta}^{s*} U_{n\alpha}^{d*} U_{n\beta}^d \right) \right]. \end{aligned} \quad (6)$$

For two neutrino flavors and with CP conservation we have

$$U = \begin{pmatrix} \cos \theta_{ms} & -\sin \theta_{ms} \\ \sin \theta_{ms} & \cos \theta_{ms} \end{pmatrix}, \quad V = \begin{pmatrix} \cos \theta_{md} & -\sin \theta_{md} \\ \sin \theta_{md} & \cos \theta_{md} \end{pmatrix}, \quad (7)$$

with  $|\theta_{ms}|, |\theta_{md}| \leq \pi/4$ . Define

$$x \equiv \frac{\Delta m^2 t}{4E}, \quad \Delta m^2 \equiv m_1^2 - m_2^2, \quad \theta_{sd} \equiv \theta_{md} - \theta_{ms}. \quad (8)$$

Using  $E_\alpha - E_\beta \approx (m_\alpha^2 - m_\beta^2)/2E$ , we get our main result:

$$P_{e\mu}(x) = \sin^2 \theta_{sd} + \sin 2\theta_{md} \sin 2\theta_{ms} \sin^2 x. \quad (9)$$

Few points are in order:

1. When neutrino interactions are described by the SM,  $\theta_{md} = \theta_{ms} = \theta$ , and Eq.(9) reduces to the known result,  $P_{e\mu}(x) = \sin^2 2\theta \sin^2 x$  [1].
2. NP that affects the production and the detection processes in the same way cannot be detected in appearance experiments. In those cases the flavor eigenstates are the same for all processes, even if they may differ from the weak eigenstates. Then we have,  $\theta_{md} = \theta_{ms}$  and Eq.(9) reduces again to the standard form, so that we cannot distinguish this situation from the SM interaction case.
3. Experiments are working with neutrino beams, not necessarily monoenergetic.  $P_{e\mu}^{exp}$  is defined to be the total appearance probability of a specific experiment, where the dependence on the energy spectrum of the beam and on the baseline length  $L$ , is included. If neutrinos are produced by several decays of different initial states, then

$$P_{e\mu}^{exp} = \sum_i a_i \tilde{P}_{e\mu}^{exp}(i), \quad (10)$$

where  $a_i$  is the relative weight of the  $i$ 'th decay mode in the neutrino beam, and  $\tilde{P}_{e\mu}^{exp}(i)$  is the appearance probability had only the  $i$ 'th decay mode been responsible for the neutrino production.

4. In two limits,  $\Delta m^2 \gg E/L$  ( $x \rightarrow \infty$ ) and  $\Delta m^2 = 0$  ( $x = 0$ ),  $P_{e\mu}$  is  $x$  independent. When  $x$  is large,  $\sin^2 x$  averages to  $\frac{1}{2}$ , then Eq.(9) gives

$$P_{e\mu} = \sin^2 \theta_{sd} + \frac{1}{2} \sin 2\theta_{ms} \sin 2\theta_{md}. \quad (11)$$

For massless (or degenerate) neutrinos,  $x = 0$  and the appearance probability becomes

$$P_{e\mu} = \sin^2 \theta_{sd}. \quad (12)$$

We learn that a signal can be seen in appearance experiments even for massless neutrinos. This is the case when  $\theta_{sd} \neq 0$ , namely, when the interaction in the production process is different from the interaction of the detection process. This signal is constant in distance, and does not have an oscillation pattern. We conclude: *a distance-independent signal is not enough to prove that neutrinos are massive. Only an oscillation pattern provides a proof.*

Experimentally, we know that neutrino interactions are dominantly those of the SM. Therefore, while  $\theta_{ms}$  and  $\theta_{md}$  may be large, their difference has to be small. It is therefore reasonable to work in the weak basis and treat the NP as a perturbation. In the two generation case we define two small angles,  $\theta_{Ws}$  and  $\theta_{Wd}$ , that parameterize the deviation from the weak basis, and a third angle (not necessarily small)  $\theta_{Wm}$ , that rotates from the weak to the mass basis. Using  $\theta_{ab} + \theta_{bc} = \theta_{ac}$  and  $\theta_{ab} = -\theta_{ba}$ , we get the relations between these angles and those defined in (7):  $\theta_{sd} = \theta_{Wd} - \theta_{Ws}$  and  $\theta_{md} = \theta_{Wd} - \theta_{Wm}$ .

To find the rotation angles we use the previously mentioned example, but the final result is general. We consider a muon neutrino beam produced by  $\pi \rightarrow \mu\nu$  decay, while the subsequent electron neutrinos are detected through  $\nu n \rightarrow ep$ . For SM interactions the produced neutrinos are  $\nu_\mu^W$ , and the detected ones are  $\nu_e^W$ . We are interested in NP that gives effective couplings of the form  $G_N^s \bar{u}d\bar{\mu}\nu_e^W$  and  $G_N^d \bar{u}d\bar{e}\nu_\mu^W$  with  $|G_N^s| \neq |G_N^d|$ . Then, the produced and detected neutrinos are superpositions of weak eigenstates,  $\nu_\mu^s \sim G_F\nu_\mu^W + G_N^s\nu_e^W$  and  $\nu_e^d \sim G_F\nu_e^W + G_N^d\nu_\mu^W$ , and it follows that

$$\theta_{Ws} \sim \frac{G_N^s}{G_F}, \quad \theta_{Wd} \sim \frac{G_N^d}{G_F}. \quad (13)$$

It is useful to express the appearance probability in terms of the rotation angle from the weak to the mass basis,  $\theta_{Wm}$ , and the NP strength,  $G_N^s$  and  $G_N^d$ . For  $x = 0$  we get from (12)

$$P_{e\mu} \approx \left( \frac{G_N^s - G_N^d}{G_F} \right)^2. \quad (14)$$

Experimentally we know that in the  $x \rightarrow \infty$  limit all the relevant angles are small. Then we get from (11)

$$P_{e\mu} \approx \left( \frac{G_N^s}{G_F} \right)^2 + \left( \frac{G_N^d}{G_F} \right)^2 + 2\theta_{Wm} \left( \frac{G_N^s + G_N^d}{G_F} \right) + 2\theta_{Wm}^2. \quad (15)$$

From the above formulae we can obtain an order of magnitude estimate of the strength of the experimentally relevant NP. An experiment with sensitivity to oscillation probability  $P_{e\mu}^{exp}$  can probe NP in neutrino interactions when its effective strength  $G_N \sim \max(G_N^s, G_N^d)$  satisfies

$$\left( \frac{G_N}{G_F} \right)^2 \gtrsim P_{e\mu}^{exp}. \quad (16)$$

### III. BRANCHING RATIO

Measurements of Branching Ratios (BR) are widely used in searching for NP effects. The meaning of BR is unambiguous when discussing quarks and charged leptons, for which a BR measures the transition rate between mass eigenstates. The main advantage of using BR is that only the production process is relevant to the calculation, and one need not worry how the decay products are detected. Therefore, measuring a BR has to be independent of

the experimental setup and of the theoretical model under study. Since experiments cannot detect neutrinos as mass eigenstates, for neutrinos these requirements are not satisfied: the time evolution of the flavor eigenstates, and the NP effects in the detection process cannot, in general, be separated from the analysis of the experimental results. Therefore, the extension of the BR notion to the neutrino case is problematic.

We see three major disadvantages in using BR for neutrinos:

1. Using BR calculations we can probe only part of the parameter space. In the two generation case three parameters describe the results of the neutrino oscillation experiments (see Eq.(9)):  $\Delta m^2$ ,  $\theta_{ms}$  and  $\theta_{md}$ . The BR calculation is sensitive only to one parameter, the mixing angle that rotate from the source basis into the basis we are interested in. For example, the BR into final mass eigenstate is given by  $\text{BR}(\pi \rightarrow \mu \nu_1^m) = \sin^2 \theta_{ms}$ .
2. In order to compare BR calculations with experiments, the dependence of the experimental results on  $\Delta m^2$  and  $\theta_{md}$  has to be removed. However, this cannot be done in a model independent way since each kind of NP may contribute differently to neutrino masses and to the detection process. Therefore, experimental measurements of BR cannot be presented in a model independent way.
3. Finally, there is a problem of definition. Are the theoretical calculations and the experimental bounds on rare decays as  $\text{BR}(\pi \rightarrow \mu \nu_e)$  [2,3],  $\text{BR}(K \rightarrow \mu \nu_e)$  [4] and  $\text{BR}(\mu \rightarrow e \bar{\nu}_e \nu_\mu)$  [5,6,3] related to the same quantities and therefore directly comparable? Calculations were done for neutrinos in the weak basis [7], and in the mass basis [8,9]. Experimental results are presented as bounds on the relative appearance probability,  $\tilde{P}_{e\mu}^{exp}(i) = P_{e\mu}^{exp}/a_i$ , where  $a_i$  is the relative weight of the relevant decay mode in the neutrino beam. In the  $x \rightarrow 0$  limit they correspond to bounds on the BR for neutrinos in the detector basis, *e.g.*  $\text{BR}(\pi \rightarrow \mu \nu_e^d)$ . In the  $x \rightarrow \infty$  limit, all the relevant angles are small, and  $\nu_1^m$  ( $\nu_2^m$ ) couples mainly to the electron (muon). Then, to first order in small angles, electrons are detected when  $\nu_1^m$  is produced at the source, or when  $\nu_2^m$  creates an electron at the detector. Therefore, the experimental results bound the sum of the rare BR in the production process and the ratio of the cross sections in the detecting process, *e.g.*  $\text{BR}^{exp}(\pi \rightarrow \mu \nu_e) = \text{BR}(\pi \rightarrow \mu \nu_1^m) + \sigma(\nu_2^m n \rightarrow ep)/\sigma(\nu_1^m n \rightarrow ep)$ . We see that the calculations cannot be directly compared with the published experimental bounds.

We conclude: The notion of BR can be used to probe only part of the parameter space. The BR cannot be measured in a model independent way, and comparisons of experimental and theoretical results have to be done always very carefully, paying attention to check that the definitions are consistent. Therefore, the notion of BR is not appropriate when searching for NP in neutrino oscillation experiments, and the formalism that we have developed here is preferable.

#### IV. EXAMPLES

We give now three examples of NP scenarios with non-standard neutrino interactions that can be probed by current and near future neutrino oscillation experiments. In each

case we first briefly present the model and the new neutrino interaction, then we discuss the actual experiment for probing the new interaction. Then, we find the neutrino sector independent experimental constraints on the strength on the new interaction, and show how results of neutrino oscillation experiments can put stronger bounds on it in part of the neutrino sector parameter space. For simplicity, we do not specify the NP responsible for neutrino masses.

In the first example we consider the Minimal Supersymmetric SM (MSSM) without R-Parity [10,11]. We consider a very simple case where the MSSM superpotential is extended with only one extra term,  $\lambda_{123}[L_L^1, L_L^2]\bar{E}_R^3$ , where  $L_L^i$  ( $E_R^i$ ) are lepton doublet (singlet) supermultiplets. Via the exchange of the singlet charged scalar,  $\tilde{\tau}_R = \tilde{E}_R^3$ , such a term gives rise to the effective four fermion interaction (in the weak basis) [11]

$$\mathcal{L} = G_N (\bar{\mu}\gamma_\lambda P_L e) (\bar{\nu}_\mu^W \gamma^\lambda P_L \nu_e^W) + \text{h.c.}, \quad (17)$$

where  $P_L = (1 - \gamma_5)/2$  and  $G_N \sim |\lambda_{123}|^2/m_{\tilde{\tau}_R}^2$ . (Recall: in the SM  $\mathcal{L}_{SM} = \mathcal{L}(\nu_\mu \leftrightarrow \nu_e, G_N \rightarrow G_F)$ .) Let us now consider the KARMEN experiment [3]. Muon anti-neutrinos are produced in muon decay,  $\mu^+ \rightarrow e^+ \nu_e^s \bar{\nu}_\mu^s$ , and electron anti-neutrinos are searched through inverse beta decay,  $\bar{\nu}_e^d p \rightarrow e^+ n$ . Since  $\tilde{\tau}_R$  couples only to leptons, the detector basis coincides with the weak basis, but the source basis is different. Muon decay is mediated by  $W$  or  $\tilde{\tau}_R$  exchange. In the weak basis, the  $W$  diagram produces  $\bar{\nu}_\mu^W$ , while the  $\tilde{\tau}_R$  diagram produces  $\bar{\nu}_e^W$ . The strongest neutrino sector independent bound on  $G_N$  is obtained from tests of universality in  $\mu$  and  $\beta$  decays [12,11]. From the lower bound [13],  $\sum_{i=1}^3 |V_{ui}|^2 > 0.995$ , we get

$$\sin^2 \theta_{sW} \sim \left( \frac{G_N}{G_F} \right)^2 \lesssim 5 \times 10^{-3}. \quad (18)$$

We like to show how the recent 90% CL bound from KARMEN [3]

$$P_{e\mu} \leq 3.1 \times 10^{-3}, \quad (19)$$

can be used to set stronger bounds on  $G_N$  in part of the neutrino sector parameter space. We study two limiting cases. For massless neutrinos, from Eq.(14) we get the bound

$$\left( \frac{G_N}{G_F} \right)^2 \lesssim 3.1 \times 10^{-3}, \quad (20)$$

which is stronger than the bound (18). In the large  $\Delta m^2$  limit, from Eq.(15) we get the combine bound

$$\left( \frac{G_N}{G_F} \right)^2 + 2 \left( \frac{G_N}{G_F} \right) \theta_{mW} + 2\theta_{mW}^2 \lesssim 3.1 \times 10^{-3}. \quad (21)$$

In the second example we consider the minimal Left Right Symmetric (LRS) model [14]. In this model there is a Higgs triplet,  $\Delta_L$ , with the Yukawa couplings to leptons (in the weak basis),  $\mathcal{L} = f_{ij} L_i^T C i \tau_2 \Delta_L P_L L_j$ , where  $L_i$  are the lepton doublets and  $C$  is the charge conjugation matrix.  $\Delta_L^+$  exchange leads to the effective four fermion interaction in Eq.(17) but with  $G_N \sim |f_{11} f_{22}|/m_{\Delta_L^+}^2$ . We again consider the KARMEN experiment. Since  $\Delta_L$

couples only to leptons, the detector basis coincides with the weak basis, but the source basis is different. Muon decay is mediated by  $W$  or  $\Delta_L^+$  exchange. In the weak basis, the  $W$  diagram produces  $\bar{\nu}_\mu^W$ , while the  $\Delta_L^+$  diagram produces  $\bar{\nu}_e^W$ . The strongest neutrino sector independent bound on  $G_N$  is obtained from tests of universality in  $\mu$  and  $\beta$  decays and is given in Eq.(18). Therefore, the bounds (20) and (21) also hold for the effective interaction arising from  $\Delta_L^+$  exchange in the minimal LRS model.

In the third example we consider models with light leptoquarks (LQ) [15]. There are several types of LQ that can lead to sufficiently large new neutrino interaction. We concentrate on the  $(I_3)_Y = (0)_{1/3}$  scalar LQ,  $S$ , which couples to fermions (in the weak basis),  $\mathcal{L} = \lambda_{ij} \bar{Q}_j^c i \tau_2 P_L L_i S$ , where  $Q_i$  ( $L_i$ ) are the quark (lepton) doublets.  $S$  exchange leads to the effective four fermion interaction (in the weak basis)

$$\mathcal{L} = G_N \left[ (\bar{u} \gamma_\mu P_L d) (\bar{\nu}_\tau^W \gamma_\mu P_L \mu) + (\bar{d} \gamma_\mu P_L u) (\bar{\nu}_\mu^W \gamma_\mu P_L \tau) \right] + \text{h.c.} \quad (22)$$

with  $G_N \sim |\lambda_{21} \lambda_{31}| / m_{LQ}^2$ . We assume  $\lambda_{32} \ll \lambda_{31}$ . Therefore, LQ interactions involving strange quarks are negligible. Let us consider the CHORUS, NOMAD and E803 experiments [16]. Muon neutrinos are produced in pion and kaon decays,  $\pi \rightarrow \mu \nu$  and  $K \rightarrow \mu \nu$ , and tau neutrinos are searched through  $\nu n \rightarrow \tau p$ . The new interaction (22) contributes the same to pion decay and to the detection process. Therefore, the neutrino produced in pion decay is  $\nu_\mu^d$ . This illustrates the above mentioned result: had the neutrino beam been produced only from pion decay, we could not probe LQ exchange in those experiments. However, the new interactions (22) do not contribute to kaon decay and the neutrino produced in  $K \rightarrow \mu \nu$  is a weak eigenstate muon neutrino,  $\nu_\mu^W$ . The strongest neutrino sector independent bound on  $G_N$  is obtained from the bound on  $\text{BR}(\tau \rightarrow \pi^0 \mu)$  [7]

$$\left( \frac{G_N}{G_F} \right)^2 \approx \frac{\text{BR}(\tau \rightarrow \pi^0 \mu)}{2 \text{BR}(\tau \rightarrow \pi^- \nu)}. \quad (23)$$

Using [13]  $\text{BR}(\tau \rightarrow \pi^0 \mu) < 4.4 \times 10^{-5}$  and  $\text{BR}(\tau \rightarrow \pi^- \nu) \approx 0.117$  we get

$$\sin^2 \theta_{dW} \sim \left( \frac{G_N}{G_F} \right)^2 \lesssim 2 \times 10^{-4}. \quad (24)$$

We like to show how the expected sensitivity of CHORUS and NOMAD,  $P_{\mu\tau}^{exp} \sim 10^{-4}$  and E803,  $P_{\mu\tau}^{exp} \sim 10^{-5}$  [16] can be used to probe LQ exchange in part of the neutrino sector parameter space. Since we concentrate on LQ that can be tested only by neutrinos from kaon decay, we have to use the relative appearance probability of neutrinos from kaon decay, where we expect  $\tilde{P}_{\mu\tau}^{exp}(K \rightarrow \mu \nu) = \text{few} \times P_{\mu\tau}^{exp}$ . We learn that LQ exchange can be tested, probably at CHORUS and NOMAD, and certainly by E803. For example, assuming that the bound  $\tilde{P}_{\mu\tau}^{exp}(K \rightarrow \mu \nu) \lesssim 5 \times 10^{-5}$  will be achieved by E803. For massless neutrinos, Eq.(14) gives

$$\left( \frac{G_N}{G_F} \right)^2 \lesssim 5 \times 10^{-5}, \quad (25)$$

which is stronger than the bound (24). In the large  $\Delta m^2$  limit, Eq.(15) gives

$$\left( \frac{G_N}{G_F} \right)^2 + 2 \left( \frac{G_N}{G_F} \right) \theta_{mW} + 2 \theta_{mW}^2 \lesssim 5 \times 10^{-5}. \quad (26)$$



## V. SUMMARY

There are two important ways in which physics beyond the SM can affect the neutrino sector: It may give non-vanishing neutrino masses, and it may modify neutrino interactions. In this paper we showed how neutrino oscillation experiments probe both effects, and how they can be distinguished in some cases. A distance-independent signal can arise from both effects. However, an oscillation pattern can arise *only* when neutrinos are massive. We study the condition on the relative strength of the non-standard neutrino interactions in order that it can be tested (see Eq.(16)). Thus, current experiments aimed to reach a sensitivity of the order  $P_{ij}^{exp} \approx 10^{-4}$  [16] can typically probe new neutrino interactions arising from physics at the 1 TeV scale. There are several well motivated NP scenarios that introduce non-diagonal couplings that can be probed in this way. Higgs triplet exchange in Left-Right Symmetric models [14], Light leptoquarks exchange in various models [15] and super-particles exchange in Supersymmetric models without R-parity [10,11].

Our results are of particular interest in light of the growing evidences for physics beyond the SM in the neutrino sector, in particular, the solar neutrino problem [1,17], the atmospheric neutrino deficit [18] and the recent LSND result [19]. Those results cannot be simultaneously accounted for in a simple three generation model, but only in models with more parameters. Usually, it is suggested that those results are hints to models with an extended neutrino sector [20]. Alternatively, it might be that they signal NP in neutrino interactions. Such NP can be significant for the MSW solution of the solar neutrino problem [12,21], for atmospheric neutrinos [22] and, as we have discussed, for accelerator experiments. A comprehensive analysis of all these experiments, including possible NP, is needed.

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